Paper Folding Bio-Kinetic Façade: Application of Bat Wing Inspired Façade Design to the Building of Mediterranean University in Tirana, Albania

Anna Yunitsyna[1], Lorena Lika

[1]*Department of Architecture, EPOKA University, Albania*

ABSTRACT

Design of kinetic and adaptable building shells is one of the recent trends in sustainable construction. In this research the main topic is the application of the foldable and nature inspired kinetic facade onto the contemporary building in Tirana and evaluation of its advantages in terms of the light control and reduction of the cooling loads of the building. The paper starts from the overview of a history of kinetic architecture. Paper folding is selected as a technique and biomimicry is an approach which helps to design the repetitive units of the facade. The chosen form of nature and the source for the design inspiration is a bat wing. The anatomy of the wing has been adapted for the project and the mathematical calculation was done in order to get the facade module, which is flexible, foldable and which can be closed and opened using the movement which is similar to the bad wing. For the application it is selected the building which currently has the glass facade with very minor shading system. The adaptable kinetic facade is constructed using the series of modules. The calculation of solar radiation was done for the several models with different percentage of openness. The new building skin allows to have the better quality of light and regulates loss and gain of heat without wasting energy.

Keywords: Biomimicry, kinetic facade, origami technique, responsive facade, sustainable design

INTRODUCTION

One of the biggest problems today is the greenhouse effect. There have been a lot of discussions on about what is needed to do to minimize this effect and its damage. One of the responses of these challenge in architecture is the interactive skin of the building that allow to get the best light with the least amount of heat in building and changes immediately according to the climate conditions. Paper folding is often used as a kind of intermediate tool even to create foldable/changing houses. The paper folding art is with an eastern origin, and it has in its focus the mimicry of nature. The word kinetic, as a term, has not been used in architecture until 1961, and even than it didn't have a really deep understanding among architects on the possibilities it offered and kinetic architecture wasn't yet neither understood as such, nor named adequately. The meaning of the word kinetic is relating to or resulting from motion. At the beginning of the twentieth century kinetic architecture started to be explored and people became aware of the term as an architectural term while before the term "kinetic" was widely used in physics [1]. Firstly, movable structures and covers in buildings were used mostly for safety and privacy reasons. Kinetic architecture was seen as a mobility of a structure or part of the structure providing the adaptability with the surroundings. Kinetic architecture was present in the middle-ages in the form of drawbridges, which were used for connecting the castle to the ground for protection purposes [2]. Today besides the drawbridges it is known a large variety of kinetic bridges such as bascule and rolling bascule bridge, folding, curling, retractable, submersible, tilt, swing, transporter and vertical lift bridge. Until the eighteenth and nineteenth centuries, there weren't many uses of kinetics in architecture besides doors, window or roofs. Nowadays kinetic architecture is getting more and more advanced, starting from kinetic doors, facades and roofs to whole moving houses. During the last decade there has been a growing interest in dynamic architecture, starting from louvers to the whole facades. The aim of a lot of this research is to present a changeable architecture that responds to the different needs throughout the day and time using the adaptable skins and materials. The variety of the kinetic facades can be classified according to the technique which is used to achieve the changeability.

USE OF BIOMIMICRY IN ORIGAMI DESIGN

The first term used was biomimetics, which was used to describe the transfer of ideas from biology to technology, then it became biomimicry. Another term used was bionics which than became associated more with robotics [3]. From ancient times people tried to imitate and learn from nature. Leonardo Da Vinci made the first drawings of a flying object (plane) imitating the wings of a bird. But, while they imitated nature and biology, it was still only the form finding. A new type of mimicking the nature started when people became to study how the natural processes work and why. Instead of mimicking the form, they started to study and mimic the process.

Origami is the ancient Japanese art of paper – folding. It comes from the word "ori" – folding and the word "kami" – paper. Today, origami comes in many shapes and forms, and also different techniques. Origami artist today use both ancient techniques, either with strategic cuts or just strategic paper creasing, and employ them in their own way. Many techniques exist today that have derived from the original ones [4]. Among all the origami techniques can be noted the Pureland origami, where there are used only the simple mountain/valley folds, and each of these folds must have a straightforward location. The second type of origami which is suitable for the kinetic architecture is origami tessellation which uses the repeated pattern of folds [5]. The most used pattern and origami technique in architecture is the Miura - Ori pattern (or the Miura fold). This fold has the ability to be folded in a very compact area, the thickness of which is only restricted by the thickness of the material. This pattern can be said to be rigid origami. It can be folded from a single sheet of paper and it is the same repeated form folding in itself. When closed it takes a rigid form, depending on the kind of pattern deployed, while when unfolded is a straight sheet of paper. The folds act as hinges. Usually the new folding patterns are designed based on the traditional ones, such as Miura-Ori or Waterbomb pattern. It is really complicated to create the new flat-foldable pattern. Each of the new designs should be manually folded in order to confirm the foldability [6].

The folding can also be found in living organisms, such as insects and birds wings, it is also typical for the leaves and petals. The folding patterns from nature can be transferred into the artificial structures. The main principles of the construction are its deployability, which means that the patterns should be constructed from a single flat sheet of paper, planarity of the faces and edges and transformation of joints and folds into hinges [7]. The pattern of folds can be organized in such a way that it provides the opening and closing of the material sheet only in one direction [8]. Folding method can be used in order to compose modular and responsive building skin (Figure 1). As an example, the modular conical plywood panels with the hygroscopically responsive elements were applied in ''HygroSkin - Meteosensitive Pavilion''. The panels are able to close or open depending on the weather conditions and the indoor microclimate, such as indoor and outdoor air temperature, humidity or solar radiation [9]. The idea of the self-regulating facade was applied also in the prototype pavilion, which was constructed using the ''Breazing Skins'' technology. What this skin essentially does is the adjustment of the flow of substances (heat, light, moisture) from inside and/to outside, regulating the amount of transfer of these substances to create a better quality of ambient. The skin is made up of a system of pneumatic muscles that regulate the amount of heat, light and visibility in the structure [10]. The skin of One Ocean pavilion is built by thin sheets of glass fibre reinforced polymers, which allows for changing in different animated patterns. The skin is much like fish fins and make it possible for the structure to breathe through it by opening and closing in a kind of rippling effect [11]. Kinetic facade constructed by the honeycomb panels was applied in Al Bahar Towers in Aby-Dhabi. The hexagonal modules are constructed by six panels which can fold and unfold thus blocking or allowing the light and exchange of heat according to the needs of the indoor environment [12]. The foldable rectangular aluminium panels are applied in Kiefer Technic Showroom. Its façade is a curtain wall system that opens and closes in itself to regulate the amount of light that passes in accordance to the needs of the indoor environment. At the same time the facade can be controlled manually by the residents [13]. In the building of Syddansk University perforated triangular panels are applied as light control system. The panels are able to rotate using the vertical side as the rotation edge [14].

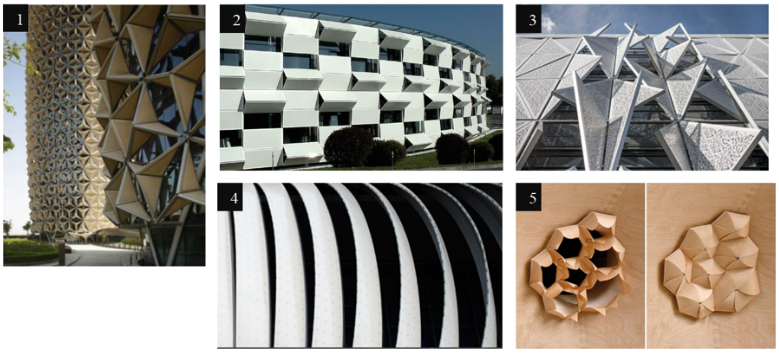


Figure 1. Kinetic facades of Al Bahar Towers (1), Kiefer Technic Showroom (2), Syddansk University (3), One Ocean Pavillion (4) and HygroSkin Pavilion (5).

ORIGAMI FAÇADE DEVELOPMENT

Case Study Selection

The selected site is the Mediterranean University building (Figure 2) which is located at Bulevard Gjergj Fishta in Tirana near the UET (European University of Tirana) and Tirana University. The reason for choosing this building as a study object is because of its façade made entirely of glass. Since it is a university, it is crucial that the light quality is good and there is no glare. Also, the heating and cooling loads are high, and it is necessary to use control the microclimate inside of the building in order to provide the comfortable environment. Currently there is a system of horizontal louvres covering the building facade, but it seems to be not efficient since there are used the curtains to control the light inside the classrooms. The building has a shape of narrow and tall cuboid. This increases the problem of the quality of the light, since there is lighter than needed for the shallow rooms. The building has six floors in total and it the highest object around. One site of the site is completely free of building and facing the street.

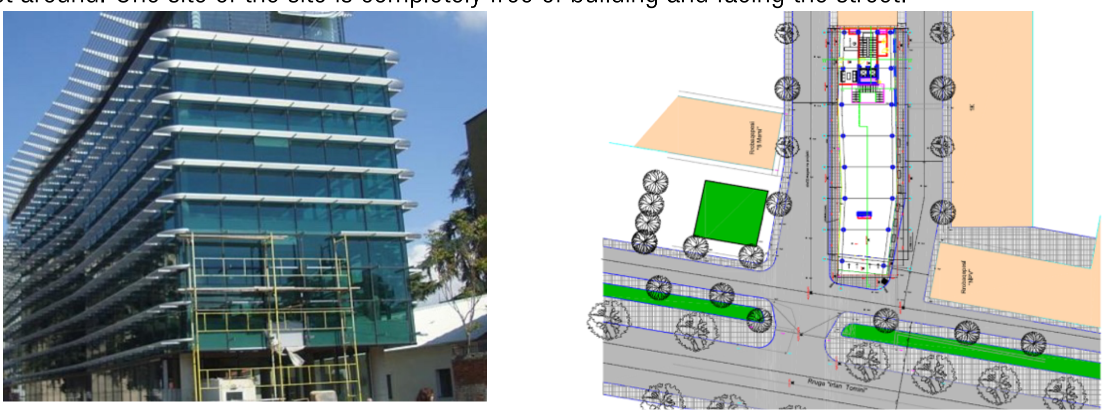


Figure 2. Glass facade of the Mediterranean University (left) and ground floor plan (right).

Development of the Origami-Folding Modular Façade Panel

The foldable module of the kinetic facade needs to satisfy three main conditions: to be open, semi-open, and closed, in order to allow different amounts of sunlight to enter the building. It also needs to be fluid and have a smooth movement which helps to pass easily through these three main fazes. One of the first things that comes to mind when thinking about fluid motions, are the wings of birds. Their wings also have these three main states; while the birds start to take flight (semi-open), while flying (open) and while resting (closed). While in flight the wing can bend and move in different angles, thus creating other intermediate phases. The bat wings have some specific details in anatomy and in movement that are much more useful in this study.

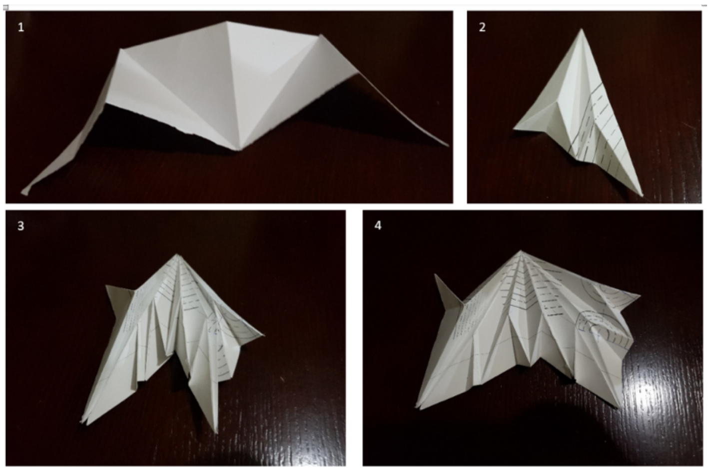


Figure 3. Partial paper models of the origami bat wing (1, 2) and full model in semi-opened (4) and semi-closed (3) positions.

The structure of the bat wing is a unique system which is combined by the bones which can be deformed during the flight. The bones are connected by over 20 flexible joints and covered by the anisotropic wing membrane [15]. Their unique anatomy makes the bat wings very flexible, and able to change position in different degrees in but a short moment of time. Despite the delicate look, the membrane is very strong. Different from bird that have stiff wing bone structure, in bats, the bone structure allows divided in three main bones, allows for a very swift and smooth movement. Another important thing is that their wings can flatten into a maximum opening, which none of the other winged beings can do, and provide the unique capacity of powered flight [16].

The origami/paper-folding art is used as a tool for translating the form of the bat wing to be used as a façade module. The study started from the origami tessellation of the part of the wing, while trying to understand the math and the rules behind the tessellation. To better understand the movements and the mechanics of it, models of the different techniques of the bat origami were needed. Below, there are pictures of the first conceptual models (Figure 3), while trying different styles, from the simplest moves to the more complicated bat wing.

Different from the majority of the origami shapes that start with a square page, the bat wing origami starts with a rectangle. Then, the folds are created according to the bat wing bone anatomy, but in a more conceptual and rigid form, turning the long three-part joint fingers in just a simple crease. The membrane of the bat wing is the paper between this simple folds. To give more flexibility to the membrane part (the paper) for closing and opening, there are needed other creases to make that part of the paper bendable and able to close. The most simplified action is to create a fold down the middle of this part of the paper (the membrane part) for giving the paper the ability to close, and three other creases between the membranes main crease and the creases related to the bone structure. This type of translation of form from nature to origami tessellation allows for a flexible and dynamic form and movement of the form. But this is the understanding a in a conceptual and mechanical (working with hands) level, while it is needed a more mathematical approach to figure out the final form so the folds will fit with each other when closing and finding the right angle to make this type of closure correct.

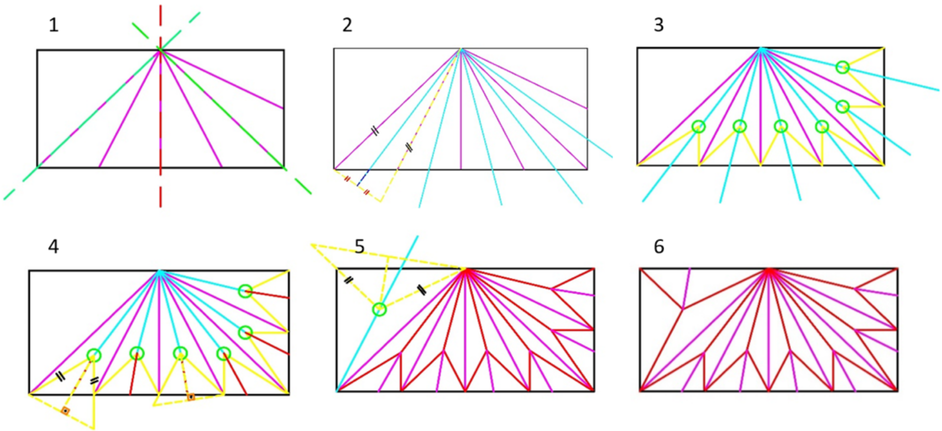


Figure 4. Stages of development of the geometry of facade module.

Origami is built on very precise mathematical calculations. One of the simplest and probably most used (most important) mathematical rules in origami are related to symmetry. Symmetrical rules make it possible for all the pieces of the paper to fit in with each other, and to fall in on itself creating a fluid movement of closing completely, and then opening to a flat surface. At the Figure 4 is explained step by step the logic behind finding the form of the façade module and the mathematics involved in it.

The first step is a rectangle piece of paper, with dimensions of the sides in ½ relation with each other. The rectangle is divided in the middle (red interrupted line), creating two equal squares. These squares get divided once more by a diagonal (green interrupted line) through each of them that pass through the upper middle point of the rectangle and intersect with the middle line. The point where they join mimics the elbow joint of the bat wing. There are four equal triangles and for the next step there will be used three of them (2), which are divided in the middle, with a line that starts from the angle where the other lines are intersecting, to the middle of the length facing that angle. The left triangle is left untouched for now because it serves as the part of the forelimb which allows for the opening and closing of the bat wing. The magenta lines make up the part of the bone structure of the bat wing. For the part of the membrane, it is needed another division in order to provide the flexibility of it. These lines (the cyan lines) are taken from the point where all the lines intersect, to the middle of the lengths in front of each angle, of the big isosceles triangle formed by extending the shortest line to make it the same as the longest line. To further deal with the flexibility of the membrane, there are needed these little triangles (3) which will fold on itself and give dynamic to the module. To build the triangles, first it is needed to find the middle point of the bigger triangles. This middle point is found by constructing a line from each angle, to the lengths in front of the angles. The intersecting point (marked with a green circle) is connected to the edges of the bigger triangles. So, find the valley (line of folding down-ward in origami), it is needed to find the right angle for the bigger triangles to fold in a symmetrical way (4). The symmetrical line of an isosceles triangle (a triangle with two equal lengths) is the line from the smallest angle of said triangle to the base, who form a right angle. So, to find the right angle the smallest length of the small triangle is elongated and made equal to the length in the front. Then it is created another triangle, which is an isosceles triangle (the yellow triangle), and the right angle which identifies the folding line. The bigger left triangle that was left untouched until now (5), mimics the forearm of the bat. It is needed to find the middle point and the folding line, following the same mathematical rules as above. The difference in this part is the direction of the fold, which allows and creates the fluid and dynamic movement, and also the ability to completely close the module. In the final image (6) it is shown the finished tessellation of the origami bat wing for the facade module. The red lines are the mountains –

the lines that are going up, while with magenta are the valleys- the lines that are going to go down during the folding process.

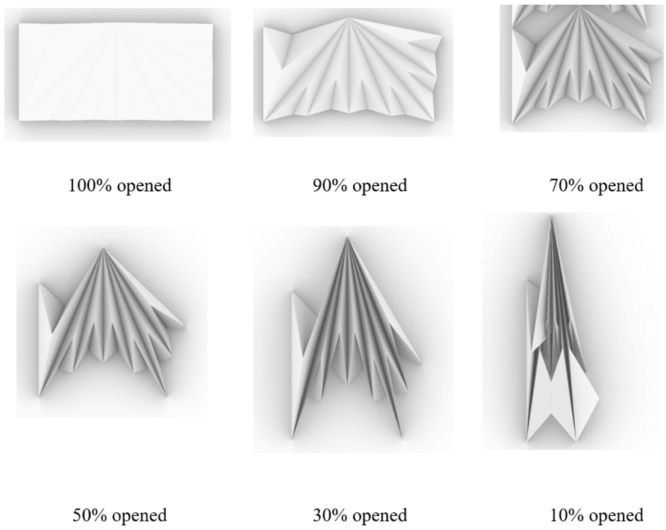


Figure 5. Simulation of opening and closing of the facade module.

The pattern of mountains and valleys was tested using the Grasshopper and Kangaroo live-physics engine. Kangaroo allows to model the objects and to simulate the behavior on them [17]. In this case it was tested the Grasshopper definition for origami folding. It is generated the set of 3d models with different level of openness/closeness, ranging from completely open to 10% closed (Figure 5).

Analysis of the Solar Radiation

The analysis of the solar radiation received by the building was performed for the variations of the origami facade with different level of openness and also for the initial glass facade of the building. The simulation was done using the Ladybug for Grasshopper, which is a tool for the wide range of environmental studies [18]. The advantage of this tool is that all the process of the design, development, model making and model evaluation is performed via Grasshopper, which means that there is no need to use any external software or to export the models of simulations (Figure 6). The solar radiation analysis was performed for Summer and Winter Solstices and Spring and Fall Equinoxes using the weather data from Albania.

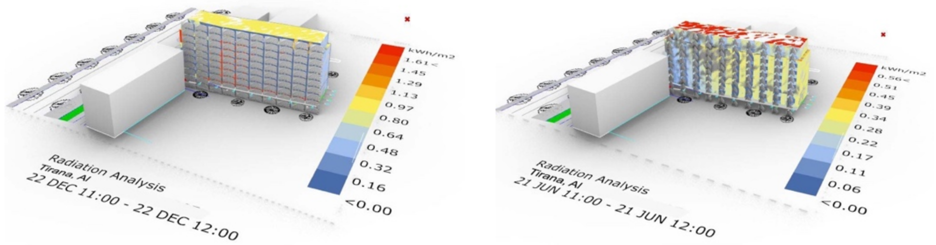
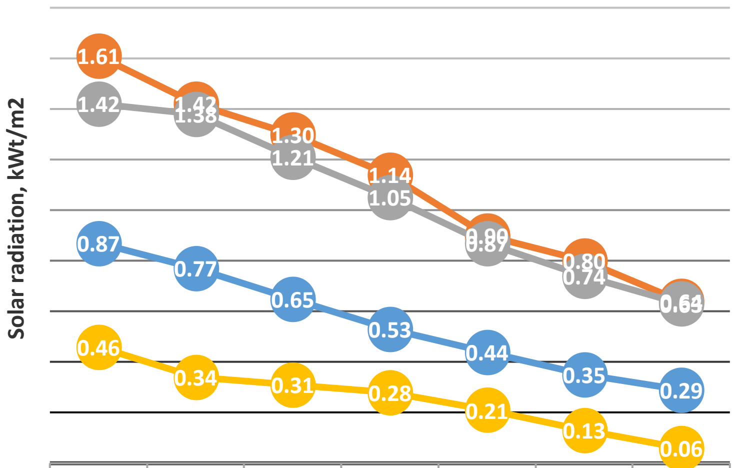


Figure 6. Solar radiation analysis of the building with different types of origami facades using Ladybug.

The results of the solar radiation analysis for the initial building and the origami folding facade in the six different stages of opening are shown in the Table 1.

From the simulation it can be noticed that the highest amount of solar radiation is received by the facade with no shading system and the amount of solar radiation is decreasing as far as the shading system is getting into the unfold position. During the Summer Solstice the building receives the highest amount of solar radiation, meanwhile the Fall Equinox has significantly higher numbers in comparison to the Spring Equinox.

Table 1. Solar radiation data



	Glass façade	0% opened2	10% opened	30% opened	50% opened	70% opened	90% opened
Spring Equinox	0.87	0.77	0.65	0.53	0.44	0.35	0.29
Summer Solstice	1.61	1.42	1.30	1.14	0.90	0.80	0.64
Fall Equinox	1.42	1.38	1.21	1.05	0.87	0.74	0.63
Winter Solstice	0.46	0.34	0.31	0.28	0.21	0.13	0.06

CONCLUSION

The research was developed in order to design a building façade that can respond to the environment, mainly the sun heat and sunlight, in a way that the building would have the best light possible and the lowest solar radiation, which would control the indoor temperature and reduce the cooling energy loads. Origami (or paper-folding art) and bio mimicry are used as methods to design the modular facade component. Origami helps to translate the chosen form from nature to module by discovering a specific tessellation that makes the project work. Biomimicry is the concept which makes possible the study of the chosen form in nature and finding of the way and the idea of the mechanics for the project. It defines how the module is going to move, what are its main positions and how much flexibility is the project going to have. The chosen form of nature to study was a bat wing, because of its flexibility in movement and the way it can take different positions during flight. The project module needed careful mathematical calculations to be built in a way that allows the parts of the module to be folded correctly, with no extra edges. The finished product has three main positions; open, semi-open, and closed; and other sub-positions (ways of opening) in different degrees.

The module is very flexible, and the opening is done by light and heat sensors attached to it to make the façade react to the environment. These sensors are what puts the façade in motion in different degrees of opening, according to the ideal light and heat that a building should have as by European standards. Application of the module can be done in different variations providing the various facade patterns (Figure 7).

The modules are connected to a metal mesh frame that envelopes the building. The modules are fixed in only one side and the other side is free to be able to move and have the needed flexibility. The selected membrane material is a carbon fiber sheets or fiber glass since it demonstrates the desired bendable ability, strength and flexibility.

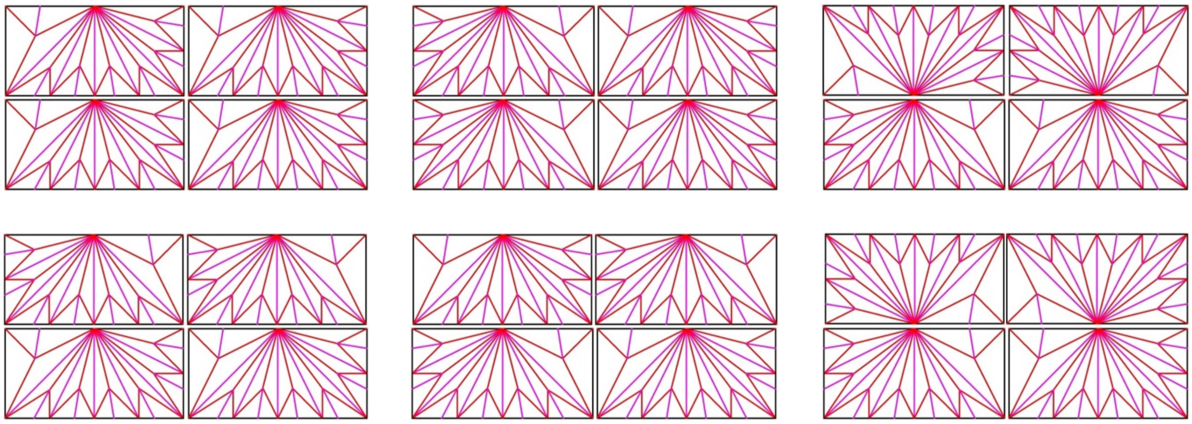


Figure 7. Façade pattern with different ccombinations of origami modules.

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